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**APPLICATION  
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LETTERS PATENT**

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FOR: MAGNETIC BEARING CONTROL DEVICE

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MAGNETIC BEARING CONTROL DEVICE

BACKGROUND OF THE INVENTION

TECHNICAL FIELD OF THE INVENTION

5       The present invention relates to a magnetic bearing control device for controlling a magnetic bearing that supports a rotor effecting high speed rotation such as TMP (Turbo Molecular Pump) in non-contact manner in a state of magnetic levitation.

10      RELATED ART

Generally, a magnetic bearing for supporting a rotor in non-contact manner is known as a bearing for the rotor effecting high speed rotation. A device using such magnetic bearing is a Turbo Molecular Pump (hereinafter referred to as "TMP") used in the semiconductor manufacturing devices, for example. The Turbo Molecular Pump typically has a machine main body (pump main body) for supporting a rotation body (rotor) constituting a pump with a control type magnetic bearing in non-contact manner and rotating it with an electric motor, and a controller 15     for controlling the machine main body.

20      (magnetic bearing control device) for controlling the machine main body.

In recent years, the TMP magnetic bearing control device as described above has a main stream changed from the conventional analog control method to digital control method 25     along with the advancements of digital technology. The related

TMP magnetic bearing control device of the digital control method is disclosed in JP-A-11-210673, for example. This related TMP magnetic bearing control device includes a DSP (Digital Signal Processor) for controlling a magnetic bearing and an electric motor, a flash memory storing a processing program and the control parameters in the DSP, and a real time clock. In the related TMP magnetic bearing control device, the DSP memorizes the operation hysteresis and the malfunction occurrence hysteresis in the flash memory with the time based on the output of real time clock, thereby facilitating the failure or malfunction diagnosis.

By the way, the Turbo Molecular Pump comprises electrical or electronic parts with relatively short service life (duration of life). More specifically, the parts with relatively short duration of life may include a large capacity electrolytic capacitor contained in a cooling fan for cooling a rotor (pump) and a control device main body or a power source circuit. The duration of life of these parts, as well as the operation time of the maintenance operation recommended by the maker, are described in the document such as an instruction manual or a specification sheet. Therefore, the related TMP magnetic bearing control device allows the maintenance operation to be practiced at the user's risk.

However, actually, in the related TMP magnetic bearing control device, because there is no operation of collating or

confirming the operation hysteresis memorized in the flash memory or the total operation time calculated from the time when the power source is turned ON to the time when it is turned OFF with respect to the duration of life described in the above 5 document, or due to the document missing, or other reasons, the appropriate maintenance operation can not be surely effected on the user's side at all times, whereby there is the possibility that it would be employed until a malfunction or failure occurred. Therefore, when the related TMP magnetic bearing control device 10 is employed, the maintenance operation can not be performed appropriately on the user's side, resulting in degraded performance or safety of the Turbo Molecular Pump.

#### SUMMARY OF THE INVENTION

15 In the light of the above-mentioned problems associated with the conventional art, it is an object of the present invention to provide a magnetic bearing control device which is capable of effecting the safety operation management and the performance maintenance of the control object devices and 20 the control device by notifying automatically the user of the operation time of the maintenance operation and prompting the user to practice the required maintenance operation.

According to a first aspect of the present invention, there is provided a magnetic bearing control device for 25 controlling a magnetic bearing for supporting a rotor in

non-contact manner, said magnetic bearing control device comprising:

a digital processor which controls at least said magnetic bearing; and

5 a counter for accumulating and counting an actual work time of a designated managed component;

wherein said digital processor performs a comparison between the accumulated actual work time of the managed component counted by said counter and a preset maintenance time, and  
10 outputs a signal indicating start of maintenance operation of said managed component on the basis of the result of the comparison.

In the magnetic bearing control device as constituted above, the digital processor performs a comparison between the  
15 accumulated actual work time of the managed component counted by the counter and the preset maintenance time, and outputs a signal indicating the start of maintenance operation of the managed component, on the basis of the result of comparison, whereby the user can be automatically notified of the operation  
20 time of maintenance operation.

According to a second aspect of the invention, in the magnetic bearing control device of the first aspect, it is preferable that said digital processor inhibits the activation of said magnetic bearing control device, after the accumulated  
25 actual work time of the managed component counted by said counter

exceeds a preset limit time.

In this case, when the user does not perform the maintenance operation, the digital processor inhibits the activation of the control device to enable the maintenance operation to be 5 compulsorily practiced.

According to a third aspect of the invention, in the magnetic bearing control device of the first or second aspect, the digital processor may comprise a function of the counter.

In this case, since the counter can be omitted, the control 10 device is reduced in the circuit size.

According to a fourth aspect of the invention, the magnetic bearing control device of one of the first to third aspects may further comprises a display portion for displaying a message or an image on the basis of said signal indicating the start 15 of maintenance operation outputted from the digital processor.

According to a fifth aspect of the invention, the magnetic bearing control device of one of the first to fourth aspects may further comprises a voice output portion for outputting a sound on the basis of said signal indicating the start of 20 maintenance operation outputted from the digital processor.

According to a sixth aspect of the invention, the magnetic bearing control device of one of the first to fifth aspects may further comprises a data input device which allows an user to set said preset maintenance time.

### BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a block diagram showing the configuration of a magnetic bearing control device according to one embodiment of the present invention.

5 Fig. 2 is a flowchart showing an operation example of the magnetic bearing control device as shown in Fig. 1.

### DETAILED DESCRIPTION OF PREFERRED EMBODIMENT

The preferred embodiments of a magnetic bearing control 10 device according to the present invention will be described below with reference to the accompanying drawings. In the following explanation, a TMP magnetic bearing control device used in a Turbo Molecular Pump is exemplified.

Fig. 1 is a block diagram showing the configuration of 15 a magnetic bearing control device according to one embodiment of the invention. In Fig. 1, the Turbo Molecular Pump has the magnetic bearing control device 1 and a pump main body 2 of this invention. The magnetic bearing control device 1 is connected to an external computer, for example, a PC (Personal Computer) 3 so that the bidirectional data communication is possible. The magnetic bearing control device 1, the pump main body 2 and the PC 3 are placed at separate locations away from each other, and connected via the cable or communication line, for example.

20 The magnetic bearing control device 1 is provided with

2000 2000 2000 2000

a displacement calculation circuit 4, a magnetic bearing drive circuit 5, an inverter 6, a cooling fan drive circuit 7, a DSP (Digital Signal Processor) board 8, a serial communication board 9, a display portion 10, and a voice output portion 11. An 5 A/D converter 12, a D/A converter 13, a counter 14, a DSP 15 as a digital processor, and a memory 16 are mounted on the DSP board 8. The magnetic bearing control device 1 contains a cooling fan 17 for cooling the control device. The magnetic bearing control device 1 is provided with a power source circuit 10 connected to the commercial AC power supply and having a DC power source for DSP 15 and a back-up power source at the time of power failure, etc. for example, and an operation switch composed of an alternate-type push button with a lamp etc. (not shown).

15 The pump main body 2 is provided with a rotor 21 constituting a pump, a displacement detecting portion 22 for detecting the displacement of the rotor 21, a magnetic bearing 23 for supporting the rotor 21 in a state of magnetic levitation, a motor 24 for driving and rotating the rotor 21, a revolution 20 number sensor 25 for detecting the number of revolutions of the rotor 21, and a cooling fan 26 for cooling the pump main body 2, which is mounted on the pump main body 2. The pump main body 2 is provided with a touch down bearing (not shown) to regulate the movable range of the rotor 21 in an axial direction 25 and a radial direction, and support the rotor 21 in contact

manner, when the pump main body 2 is stopped or the rotor 21 can not be magnetically supported in non-contact manner.

The magnetic bearing 23 includes a plurality of electromagnets (not shown) and is provided with an axial magnetic bearing and a radial magnetic bearing for supporting the rotor 21 in non-contact manner in an axial direction and a radial direction due to magnetic attractive forces of those electromagnets, respectively. The displacement detecting portion 22 includes a plurality of displacement sensors for detecting the displacement of the rotor 21 in the axial direction and the radial direction (not shown).

The motor 24 rotates the rotor 21 supported by the magnetic bearing 23 in non-contact manner, and is constituted by an induction motor, for example. The revolution number sensor 25 detects the number of revolutions of the rotor 21, and outputs a pulse signal in accordance with the detected number of revolutions, for example, to the DSP 15.

In the magnetic bearing control device 1, the displacement calculation circuit 4, the magnetic bearing drive circuit 5, the inverter 6, the DSP 15 and the cooling fan drive circuit 7 are connected to the displacement detecting portion 22, the magnetic bearing 23, the motor 24, the revolution number sensor 25 and the cooling fan 26 of the pump main body 2, which are a control object device, respectively.

The displacement calculation circuit 4 calculates the

displacements of the rotor 21 in the axial direction and the radial direction, on the basis of the output signals of a plurality of displacement sensors in the displacement detecting portion 22. The displacement calculation circuit 4 generates 5 a displacement signal corresponding to the calculated displacements in the axial direction and the radial direction, and outputs it via the A/D converter 12 to the DSP 15.

The magnetic bearing drive circuit 5 comprises a plurality of power amplifiers provided corresponding to a plurality of 10 electromagnets for the magnetic bearing 23, and supplies an exciting current to the corresponding electromagnets of the magnetic bearing 23, on the basis of a control current signal input via the D/A converter 13 from the DSP 15. Thereby, the rotor 21 is supported at a predetermined target position in 15 non-contact manner in a state of magnetic levitation by the magnetic bearing 23.

The inverter 6 controls the rotation of the motor 24 in accordance with a revolution number command signal from the DSP 15. The cooling fan drive circuit 7 controls the rotational 20 drive of the cooling fan 26 in accordance with a fan drive signal from the DSP 15.

The serial communication board 9 is connected between the memory 16 on the DSP board 8 and the external PC 3, and functions as a serial interface for effecting the serial transfer 25 of data between them.

The display portion 10 comprises a liquid crystal display, for example, and displays a message or an image including the moving picture stored in the memory 16 in accordance with a command signal from the DSP 15. The message or image displayed 5 on the display portion 10 may include the operation hysteresis information of the control device, the information indicating the operation situation of the pump main body 2, and the information concerning the maintenance management.

The voice output portion 11 comprises a speaker, and 10 outputs a predetermined sound such as an alarm sound or beep tone in accordance with a command signal from the DSP 15. The voice output portion 11 may read and utter a message displayed on the display portion 10 in voice.

The counter 14 accumulates and counts the actual work 15 time of a designated managed component, as will be described later, and comprises a clock pulse oscillator for generating a fixed clock pulse, for example, a count portion for counting the clock pulse in accordance with a command signal from the DSP 15, and a holding memory for holding the addition of the 20 time counted by the count portion as an accumulated actual work time (not shown). In the case where there are a plurality of managed components designated, the counter 14 stores each accumulated actual work time in a table format, for example, to allow the management of each managed component. The counter 25 14 adds a measured time being counted at present to the

accumulated actual work time held in the holding memory at every predetermined time (e.g., one hour) and upon a request from the DSP 15, and notifies a new accumulated actual work time to the DSP 15.

5        Besides the above, the accumulated actual work time counted by the counter 14 may be output via the DSP 15 to the memory 16 to memorize it. The counter 14 may have a so-called calendar and clock function attached to manage the current date and time, and allow the DSP 15 to refer to the current date  
10      and time, as required.

The DSP 15 controls the magnetic bearing 23, the motor 24 and the cooling fan 26 in accordance with a processing program stored in the memory 16. Specifically, the DSP 15 calculates a control current value for each electromagnet of the magnetic bearing 23 in accordance with a displacement signal input from the displacement calculation circuit 4 via the A/D converter 12, and outputs a control current signal corresponding to the control current value via the D/A converter 13 to the magnetic bearing drive circuit 5 to control the magnetic bearing 23.  
15      The DSP 15 calculates the number of revolutions of the motor 24 in accordance with a pulse signal from the revolution number sensor 25, and outputs a revolution number command signal based on the calculated number of revolutions to the inverter 6 to control the rotation of the motor 24. The DSP 15 determines  
20      the number of revolutions for driving the cooling fan 26 in  
25

accordance with the calculated number of revolutions, for example, and outputs a fan drive signal corresponding to the number of revolutions determined to the cooling fan drive circuit 7 to control the rotational drive of the cooling fan 26. Besides 5 the above, a temperature sensor may be provided in the pump main body 2, and the DSP 15 may determine the number of revolutions for driving the cooling fan 26 on the basis of the ambient temperature of the pump main body 2 obtained from the temperature sensor to control the cooling fan 26.

10       The DSP 15 performs the maintenance management of the control device and the pump main body 2 (control object device) in accordance with a processing program. Specifically, in the magnetic bearing control device 1 of this embodiment, some components having relatively short service life (duration of life) among the components such as the electrical parts or electronic parts contained in the control device and the pump main body 2, are designated as the managed components when they are shipped from the factory, and registered in the memory 16, together with the maintenance time for starting the maintenance 15 operation of the managed component which is recommended for the user and the limit time for replacing the managed component which is recommended for the user. The DSP 15 performs a comparison between the accumulated actual work time of the managed component counted by the counter 14 and the preset 20 maintenance time stored in the memory 16, and manages the 25 maintenance time stored in the memory 16, and manages the

maintenance of the managed component, based on the result of comparison. More particularly, the DSP 15 outputs a command signal, including an alarm signal that is a signal instructing the start of maintenance operation of the managed component,

5 to the display portion 10 and the voice output portion 11, when the accumulated actual work time being counted elapses over the maintenance time, for example. Thereby, the display portion 10 displays a message or an image for prompting the start of maintenance operation of the managed component. Also, the voice

10 output portion 11 outputs an alarm sound for prompting the start of maintenance operation.

The message or image prompting the start of the maintenance operation may include the information necessary for the user to perform the optimal maintenance operation, such as a way

15 of practicing the specific inspection operation of the managed component, the check items in the inspection operation, and the inspection positions. The message or image may be stored in an external data storage unit such as a hard disk contained in the PC 3, for example, in addition to the memory 16, and

20 read from the data storage unit via the serial communication board 9 by the DSP 5, as required, and displayed on the display portion 10.

In the above explanation, when the accumulated actual work time counted by the counter 14 elapses over the preset

25 maintenance time, the DSP 15 outputs an alarm signal. However,

when the accumulated actual work time counted by the counter 14 falls within a predetermined range before reaching the maintenance time, the DSP 15 may output an alarm signal to notify the operation time of the maintenance operation.

5       The DSP 15 inhibits the activation of the control device, and the drive of the pump main body 2, after the accumulated actual work time of the managed component exceeds the preset limit time, irrespective of whether an operation instruction is issued by the user on an operation switch. Further, the DSP 10 15 outputs a command signal, including a failure signal (startup disabled signal) that is a signal indicating that the activation of the control device is inhibited, to the display portion 10 and the voice output portion 11. Thereby, a message or image indicating that the control device and the pump main body 2 15 is in a state of startup disabled is displayed on the display portion 10. The voice output portion 11 outputs a beep tone indicating the startup disabled state. Note that the display portion 10 and the voice output portion 11 may notify the user of a message of the contents having a request for the replacement 20 of the managed component, in addition to the startup disabled state.

If it is detected that the accumulated actual work time counted by the counter 14 exceeds the limit time while the DSP 15 controls the driving of the pump main body 2, the DSP 15 25 outputs a failure signal to the display portion 10 and the voice

output portion 11 to notify the user of the startup disabled state, and outputs a message of the contents for stopping the driving of the pump main body 2 after a predetermined time to the display portion 10 and the voice output portion 11 to notify 5 the user that the pump main body 2 will be stopped.

Besides the above, the DSP 15 may output a command signal, including a signal instructing to display a message or an image indicating that the accumulated actual work time of the managed component reaches the limit time, to the display portion 10 10 to display the message or image, and notify the user that the activation of the control device or the driving of the pump main body 2 will be inhibited, before inhibiting the activation of the control device and the driving of the pump main body 2.

15 When the completion of maintenance operation is input into the DSP 15, the DSP 15 outputs a reset signal to the counter 14 to reset the accumulated actual work time. Note that the completion of maintenance operation is input into the DSP 15 by, for example, the user operating data input device (not shown) 20 such as a keyboard with a ten key. On the other hand, a touch panel as data input device may be provided in the display portion 10 to enter the completion of maintenance operation to the DSP 15.

In the maintenance management using the maintenance time 25 and the limit time in the DSP 15, as described above, some

components having shortest service life are registered as the managed components among the contents of the control device and the pump main body 2. When the maintenance time of these managed components elapses, the DSP 15 notify to the user the 5 operation time of the total maintenance operation for the control device and the pump main portion 2. A plurality of managed components may be registered, and the operation time of maintenance operation for each managed component may be notified to the user.

10 Examples of the managed component may include a cooling fan 26 mounted on the pump main body 2, a cooling fan 17 contained in the control device, and a large capacity electrolytic capacitor for charging in the power source circuit. The specific time set as the maintenance time and the limit time of the cooling 15 fan 26, the cooling fan 17 contained in the control device and the large capacity electrolytic capacitor for charging are 44000 hours (about five years) and 52000 hours (about six years), respectively, for example. In the magnetic bearing control device 1 of this embodiment, the managed component, the 20 maintenance time and the limit time may be additionally registered by the user operating the data input device.

The maintenance time and the limit time of the managed component should be set shorter in some cases than those preset values in the memory 16, depending on the service environments 25 or the service conditions of the managed component. Specifically,

in the cooling fan 26 and the large capacity electrolytic capacitor for charging, the maintenance time and the limit time should be set shorter in some cases than the above set time, depending on the ambient temperature or the presence or absence 5 of high frequency components of the input voltage. To cope with such cases, the magnetic bearing control device 1 of this embodiment allows the user to shorten the maintenance time and the limit time by using the data input device.

The memory 16 is preferably composed of a non-volatile 10 memory such as a flash memory, an EPROM or an EEPROM, and stores the processing program for the DSP 15, the maintenance time and the limit time for the managed component, a message or image corresponding to an alarm signal and a failure signal, and coefficients necessary for executing the processing program 15 such as the control parameter of the magnetic bearing 23 used in the processing program. The operation hysteresis information of the control device and the pump main body 2, particularly the total time of the power source being turned ON, the total time of activating the magnetic bearing 23, and the total 20 rotation time of the rotor 21 are saved, e.g., in a table format in the memory 16.

In the magnetic bearing control device 1 constituted in the above way, if the user operates an operation switch to enter an operation instruction, the DSP 15 firstly outputs a control 25 current signal via the D/A converter 13 to the magnetic bearing

drive circuit 5, drives the magnetic bearing 23 to move the rotor 21 from the touch down bearing in magnetic levitation, and support it in non-contact manner at a target position. Then, the DSP 15 outputs a revolution number command signal to the 5 inverter 6 to drive the motor 24, and rotate the rotor 21 at a desired revolution number, continuing the operation of the pump main portion 2. Thereafter, if the user operates the operation switch to enter a stop instruction, the DSP 15 outputs a rotation stop command signal for stopping the rotation to 10 the inverter 6 to stop the motor 24 and the rotor 21. Subsequently, the DSP 15 outputs an energization stop signal for stopping the energization to the electromagnets of the magnetic bearing 23, via the D/A converter 13 to the magnetic bearing drive circuit 5 to stop the magnetic bearing 23 to support the rotor 21, and 15 enable the touch down bearing to support the rotor 21.

The magnetic bearing control device 1 operates the pump main body 2 in the above manner, and performs the maintenance management of the designated managed component.

Referring now to Figs. 1 and 2, a specific operation of 20 the maintenance management in the magnetic bearing control device 1 will be described below. In the following, for the simpler explanation, the operation of the maintenance management for the cooling fan 26 will be exemplified.

Fig. 2 is a flowchart showing an operation example of 25 the magnetic bearing control device as shown in Fig. 1.

As shown in Fig. 2, the DSP 15 discriminates whether or not the power supply is turned on (step S1). If it is detected that the power supply is turned on, the DSP 15 instructs the counter 14 to count the energization time of the cooling fan

5 26. Note that an instruction from the DSP 15 to the counter 14 is performed after the DSP 15 outputs a fan drive signal instructing the cooling fan drive circuit 7 to drive the cooling fan 26. Thereby, the counter 14 can measure the time (actual work time) for which the cooling fan 26 is actually energized.

10 Subsequently, the counter 14 notifies the DSP 15 of the accumulated actual work time of the cooling fan 26 that is being counted at every predetermined time and upon a request from the DSP 15 (step S2).

Upon accepting the accumulated actual work time of the 15 cooling fan 26 from the counter 14, the DSP 15 reads the maintenance time and the limit time of the cooling fan 26 from the memory 16 and compares the accumulated actual work time with the maintenance time and the limit time (step S3). If the accumulated actual work time does not elapse the maintenance 20 time, the procedure returns to step S2.

If the accumulated actual work time of the cooling fan 26 elapses the maintenance time, the DSP 15 outputs a command signal including an alarm signal to the display portion 10 and the voice output portion 11 to prompt the user to start the 25 maintenance operation of the cooling fan 26, as described above

(step S4). Thereby, the user can be notified of the operation time of the maintenance operation of the cooling fan 26 to take up the appropriate maintenance operation.

If the accumulated actual work time of the cooling fan  
5 26 exceeds the limit time at step S3, the DSP 15 inhibits the activation of the control device and the driving of the pump main body 2, as described above, and outputs a failure signal to the display portion 10 and the voice output portion 11 (step S5). Thereby, the user is notified that the cooling fan 26 is  
10 required to be exchanged, and is compelled to perform the maintenance operation by inhibiting the activation of the control device and the driving of the pump main body 2.

As described above, in the magnetic bearing control device 1 of this embodiment, since the DSP 15 compares the accumulated  
15 actual work time of the managed component with the preset maintenance time, and outputs a signal instructing the start of the maintenance operation of the managed component, the user can be automatically notified of the operation time of the maintenance operation. Thereby, this magnetic bearing control device 1 can prompt the user to perform the maintenance operation required for the managed component, to allow for the safety operation management and the maintenance of performance of the pump main body 2 and the control device by practicing the maintenance operation.

25 In the above explanation, the magnetic bearing control

device 1 is employed for the Turbo Molecular Pump, but the invention is not limited thereto. The invention is also applicable, so far as the control device controls the magnetic bearing for supporting the rotor in non-contact manner.

5 Specifically, the magnetic bearing control device 1 of the invention is suitably applicable to a lathe with a spindle using the magnetic bearing, a machining sensor, a tool machine such as a grinder, a compressor using a magnetic bearing, a fluid machine such as a blower, and a magnetic bearing used for a  
10 fly-wheel.

In the above explanation, the digital processor is composed of the DSP 15, in which it suffices that the digital processor can control at least the magnetic bearing 23 by a predetermined processing program. Specifically, instead of the  
15 DSP 15, an MPU (microprocessor unit) may be employed as the digital processor.

In the above explanation, the counter 14 is provided separately from the DSP 15, but the present invention is not limited thereto. The DSP may implement the function of the  
20 counter of accumulating and counting the actual work time of the designated managed component. In the case where the DSP includes the function of the counter, the counter 14 can be omitted, whereby the control device is reduced in the circuit size.

25 In the above explanation, the display portion 10 and the

voice output portion 11 are provided in the magnetic bearing control device 1, but at least one of the display portion 10 and the voice output portion 11 can be omitted. For example, in a case where a message or image displayed on the display portion 10 is output via the serial communication board 9 from the memory 16 to the PC 3, and displayed on the display such as a CRT (Cathode Ray tube) connected to the PC 3, the display portion 10 can be omitted.

The method of connecting the magnetic bearing control device 1 and the PC 3 is not limited to the serial communication board 9 for making the serial transfer, but the magnetic bearing control device 1 and the PC 3 may be connected by way of a modem, for example, to effect the bidirectional data communication with the packet system.

The present invention has the following effects.

With a magnetic bearing control device according to the invention, the digital processor performs a comparison between the accumulated actual work time of the managed component counted by the counter and a preset maintenance time, and outputs a signal indicating the start of maintenance operation of the managed component, on the basis of the result of comparison, whereby the user can be automatically notified of the operation time of maintenance operation. Therefore, in the magnetic bearing control device, the user is prompted to practice the required maintenance operation, and can effect the safety

operation management and the performance maintenance of the control object devices and the control device by performing the maintenance operation.

With the magnetic bearing control device of the invention, 5 the digital processor inhibits the activation of the control device, after the accumulated actual work time of the managed component counted by the counter exceeds a preset limit time, thereby allowing the maintenance operation for the managed component to be compulsorily performed. Therefore, it is 10 possible to surely effect the safety operation management and the performance maintenance of the control object devices and the control device.

With the magnetic bearing control device of the invention, the digital processor comprises the counter. Therefore, if the 15 counter is omitted, the control device can be reduced in the circuit size.